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Cleaning space debris with a space-based laser system

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Abstract High-energy pulsed laser radiation may be the most feasible means to mitigate the threat of collision of a space station or other valuable space assets with orbital debris in the size range of 1–10 cm. Under laser irradiation, part of the debris material is ablated and provides an impulse to the debris particle. Proper direction of the impulse vector either deflects the object trajectory or forces the debris on a trajectory through the upper atmosphere, where it burns up. Most research concentrates on ground-based laser systems but pays little attention to space-based laser systems. There are drawbacks of a ground-based laser system in cleaning space debris. Therefore the placement of a laser system in space is proposed and investigated. Under assumed conditions, the elimination process of space debris is analyzed. Several factors such as laser repetition frequency, relative movement between the laser and debris, and inclination of debris particles which may exercise influence to the elimination effects are discussed. A project of a space-based laser system is proposed according to the numerical results of a computer study. The proposed laser system can eliminate debris of 1–10 cm and succeed in protecting a space station.

1. Introduction

Several organizations among the world's space-faring nations are concerned about the increasing risk of space debris interfering with operational satellites. Although no one knows when this will turn into a crisis, there is general consensus that sometime in the next one or two decades, the frequency of collision events in congested orbital regions will dramatically increase. The result will be a loss of access to an important part of space.[1–3] The debris size range of greatest potential danger and therefore interest is 1–10 cm according to results of international research. It is because on one hand debris smaller than 1 cm can be shielded to decrease damage to a spacecraft. On the other hand, there are few enough objects larger than 10 cm, so that it is generally possible to maneuver a spacecraft to avoid colliding with them.[4] Aimed at cleaning dangerous space debris, an idea was born in the United States, Germany, Australia, Russia, etc. in a succession to use the radiation of high-power lasers to annihilate dangerous particles up to several centimeters in diameter. Under laser irradiation, part of the debris material is ablated and provides an impulse to the debris particle. Proper direction of the impulse vector either deflects the object trajectory or forces the debris on a

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trajectory through the upper atmosphere, where it burns up. Some space-faring nations such as America, Russia, the European Union have done research on space debris eliminated by laser. However, most research concentrates on ground-based laser systems[4–11] but pays little attention to space-based laser systems.

There are, however, drawbacks of a ground-based system: a rather long distance, 350–1000 km, must be bridged to focus a laser beam on a particle with a radius of only a few centimeters, and an extremely high steering accuracy must be met. In addition to a formidable target detection and acquisition system, a very large beam director mirror is needed to obtain a high enough laser fluence and power density on a target to produce a noticeable impulse. A large fraction of the laser beam power will be wasted because a transmitter telescope cannot produce a small enough focal spot at these long distances. Only continued processing of a debris particle over several orbital revolutions may be sufficient to lower the orbit substantially and allow the atmosphere eventually to do its cleaning work. Another opportunity to continue the processing on a certain particle exists only when it passes over the station again. Several stations around the globe may, therefore, be preferred, if the time for final elimination should be reduced. Cleary, the system can only be used in a preventive way and cannot counter an immediate collision threat.[12]

In this work, the placement of a laser system in space is proposed and investigated. This method gives much more flexibility to counter the debris problem. Several factors such as laser repetition frequency, relative movement between the laser and debris, and inclination of debris particles which may exercise influence to the elimination effects are discussed. A project of the space-based laser system is proposed to protect space stations according to the numerical results of computer study data.

2. Profile of the space-based laser system

Direct ablation mode and ablation back-jet mode are two modes in debris eliminated using a laser. The former mode is primarily aiming at tiny debris particles, and laser energy is used to burn down debris particles. The latter mode is pointed at larger debris particles, and laser energy is used to transfer orbit of debris. Debris particles would be burned down by the drastic aerodynamic heating effect.

Ablation back-jet mode is used to clean debris of a centimeter magnitude. Laser energy would be transformed to thermal after the irradiation, and the laser spots would increase the temperature of the irradiation region to the melting or even boiling point of the debris material. The plasma produced by ablation would expand in a velocity much higher than that of sound when the temperature rises to the vaporization point. The debris particle would be exerted by a reaction force. The force would lead to object trajectory, as shown in Fig. 1. Perigee altitude of the debris is reduced after the reactions of multiple laser pulses, and the particle would be burned down by the aerodynamic heating effect.[13]

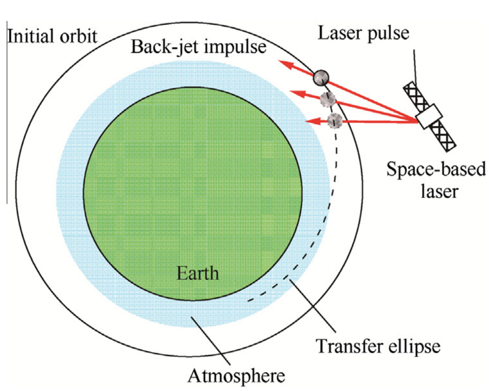

Fig. 1 Removal process of a debris particle.

A typical debris particle would reenter in a few days due to atmospheric drag if its perigee is less than 200 km. For the same debris at a 500-km perigee, the natural decay time is approximately 18 years.[1] Therefore, the 200-km altitude is defined as the threshold for successful removal.

2.1. Choice of laser beam transmission

A suitable laser should satisfy the following conditions: (1) high average power and peak power; (2) high pulse energy; (3) high laser beam quality; (4) mature technology and easy to maintain.

Possible candidates could be a solid-state laser operating in a burst mode (heat capacity laser, 1.06 μm). There is no mechanically driven component equipped in a solid-state laser and no need to refuel the system; therefore, it is particularly reliable.

The laser wavelength is λ, mirror diameter D_b, focal length z, Gaussian beam constant a', and N times diffraction limit. The diameter of the far field laser spot can be expressed as

$$d_s = a' \frac{N\lambda z}{D_b} \tag{1}$$

Assume that the laser wavelength is 1.06 μm and the pulse width is 7 ns. The focal spot should not be too small in consideration that it is difficult to track and aim a debris target. However, too large a spot causes serious energy waste and is difficult to reach the ablation threshold as well. Therefore, assume that the diameter of the far field laser spot is $d_s = 15$ cm. For a uniform plane light wave laser beam of diffraction limit $a' = 2.44$ and $N = \sqrt{2}$, maximum z is 100 km. The mirror diameter D_b can be calculated as

$$D_b = a' \frac{N\lambda z}{d_s} = 2.44 \text{ m} \tag{2}$$

Above all, the mirror diameter should be 2.44 m in order to get a 15-cm spot.

2.2. Mass model

For the changes of the motion parameters, the debris mass is the most relevant quantity, whereas the dimensions are important for the optical coverage of the debris body. Of course, the connection between these two quantities is determined by the geometry of the particle, which may be completely arbitrary.

For statistical purposes, a model has been employed. In this model, the mass is related to some power of the diameter ($m \propto d^{2.26}$). A graphical representation is given in Fig. 2, and compared with the relation for either a sphere ($m \propto d^3$) or a thin disk ($m \propto d^2$). According to this model, a 10-cm-diameter object would have a mass of 70 g if it is aluminum and 40 g if it is carbon.[12]

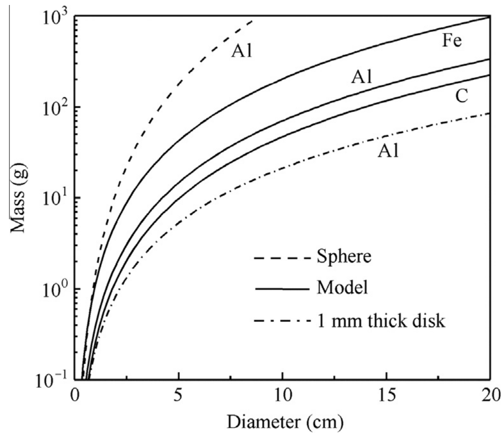

Fig. 2 Mass vs diameter for different shapes and materials.

2.3. Debris material

Aluminum and carbon are selected as typical materials of the debris. Meanwhile, most laser-material interaction data are available for them. The mechanical impulse that is exerted if some material is ablated can be related to the incident laser pulse energy E with the aid of the impulse coupling coefficient $m\Delta v = C_{\mathrm{m}}E$. A coupling coefficient $C_{\mathrm{m}} = 2\times10^{-5}$ N·s/J for Al or 1.4×10^{-5} N·s/J for C is assumed consistent according to the typical experimental results.[14–17] The coupling coefficient could be higher with the changes of laser parameters such as intensity, wavelength, and pulse length irradiated to the debris material. Ignoring the variation of laser parameters, C_{m} can be considered as a constant.

It is more difficult to find total ablation rates μ in the literature. Total ablation rates are the sum of directly vaporized and ionized materials, as well as fragmentized pieces from thermal stress in brittle materials or from the expulsion of liquid by the pressure pulse. In fact, if no precise material ablation is required, as is the case in industrial laser materials processing, expulsed liquid may make up the largest part in the ablation process.[18,19] Expulsion of liquid occurs in particular for Al and for laser pulses with pulse lengths from tens of nanoseconds up to microseconds. Knowledge of the ablation rate is important for repetitive pulse operation because, for a fixed coupling coefficient C_{m}, the achievable velocity increases with reducing mass. For the ith laser pulse, the velocity increase is $\Delta v_i = C_{\mathrm{m}}{\cdot}E/m_i$ with

$$m_i = m_0 - \sum_i \mu E \tag{3}$$

where m_0 is the initial mass, m_i the mass after laser irradiation, and E the laser pulse energy. In accordance with Lenk et al.[20] a total ablation rate $\mu = 80\times10^{-9}$ kg/J = 80 μ g/J is assumed for Al. A lower ablation rate delays the achievement of the final transfer velocity. For this reason, alternative calculations have been performed for carbon as the target material, using $C_{\mathrm{m}} = 1.38\times10^{-5}$ N·s/J and $\mu = 10.2$ μ g/J.

3. Transfer model of debris orbit

The target debris particle and the laser station are assumed to move on circular orbits, of which the orbital altitude of the laser station is H_T, the initial orbit of the debris is circular a, and the orbital altitude of the debris is H_a.

Transmission points are 1, 2, and 3. The debris transmits to orbit b after the first transmission, as shown in Fig. 3. The initial velocity before transmission is v_{a1}. The velocity increment of the debris after each transfer is Δv. For laser ablation effect, the mass of the debris particle decreases linearly and Δv increases linearly.

Simulation of the orbit transfer about the debris particle comes down to the calculation in a 3D coordinate system. The laser system moves in the xOy plane, and the orbit center coincides with the coordinate center.

Assume that the angle between the laser and the x axis is α_1, while the angle between the debris and the x axis is θ_1, as shown in Fig. 4. The laser and the debris both move along the clockwise direction. The debris locates at $(r_1{\cdot}\cos\,\theta_1,$ $r_1{\cdot}\sin\,\theta_1\,\cos\,\tau_0,\ r_1{\cdot}\sin\,\theta_1\,\sin\,\tau_0)'$ and the laser locates at $(r_T\cos\alpha_1, r_T\sin\alpha_1, 0)'$. The orbit transfer about the debris particle can be calculated in this coordinate system through dynamics equations.

4. Characteristic results

Parameters of the laser system such as laser repetition frequency and orbital parameters of the debris may exert influences to the elimination time. The total elimination time can be expressed through the model mentioned above.

4.1. Laser repetition frequency

Repetition frequency is an important parameter of the space-based laser system. Assume that the laser pulse energy is 1 kJ. It means that different laser repetition frequencies correspond to different laser powers. The higher the laser power is, the better the effect of elimination is. However, a high-power

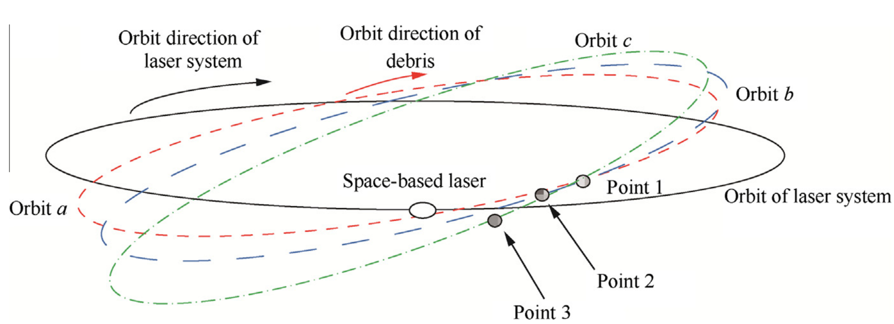

Fig. 3 Transfer process of a debris particle.

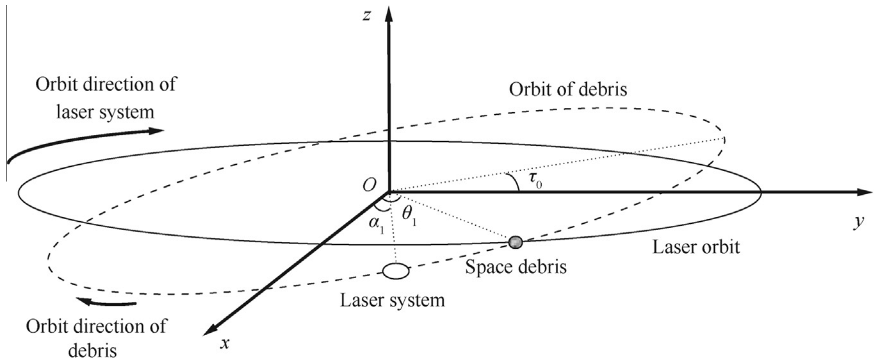

Fig. 4 Coordinate system for calculation.

Table 1 Projects of different laser repeat frequencies.

Project	Average power $\overline{P}$ (kW)	Frequency f(Hz)	Pulse energy E(kJ)	Coupling coefficient C_m(10^{-5}N·s/J)	Velocity increment Δv (m/s)
1	1	1	1	2	0.1270
2	10	10			
3	100	100			

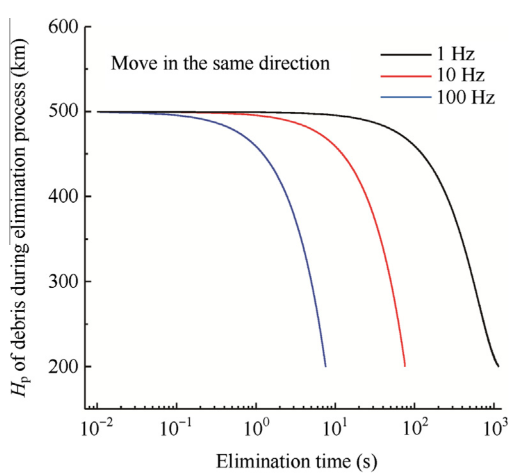

Fig. 5 Effects of laser repeat frequency.

laser would be technically challenging because heat dissipation is very difficult. The cost would increase a lot. Therefore, the choice of an appropriate laser repetition frequency is of importance to the elimination tasks.

Assume that the laser system moves in a circular orbit of 550 km. The debris particle moves in a 500-km circular orbit initially. They move in the same direction and the same orbit plane. The laser system would irradiate the target debris when the distance between them is less than 100 km and it would stop firing if the perigee altitude of the debris would not reduce after irradiation of the next laser pulse.

For an aluminum debris particle of a 10-cm diameter, the mass of the particle would be 70 g according to Fig. 2. Laser pulse energy is assumed to be 1 kJ. In comparison with the elimination time of different laser repetition frequencies, three projects are listed in Table 1.

The elimination effect of the three projects are shown in Fig. 5. The x-coordinate is elimination time. The y-coordinate is the perigee altitude H_p of debris during elimination process. It can be seen in the figure that the higher the laser repeat frequency is, the shorter the elimination time is. It would take about 1000 s to eliminate the target particle for a 1-Hz laser, and it needs less than 10 s to eliminate the particle for a 100-Hz laser. However, if the laser system and the debris particle move in the same direction, the laser system with different repetition frequencies could all succeed in eliminating the particle, because laser repeat frequency only affects the elimination time.

When the debris particle and the laser system move in opposite directions, the elimination time is limited as the relative speed between them is extremely fast. The elimination effect is shown in Fig. 6. It can be seen in the figure that lasers of 1 Hz and 10 Hz could not succeed in eliminating 10-cm-diameter debris moving in the opposite direction relative to the laser system.

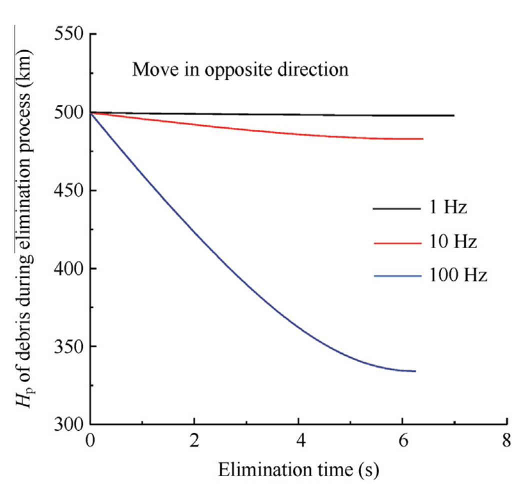

Fig. 6 Elimination effects of debris in opposite direction.

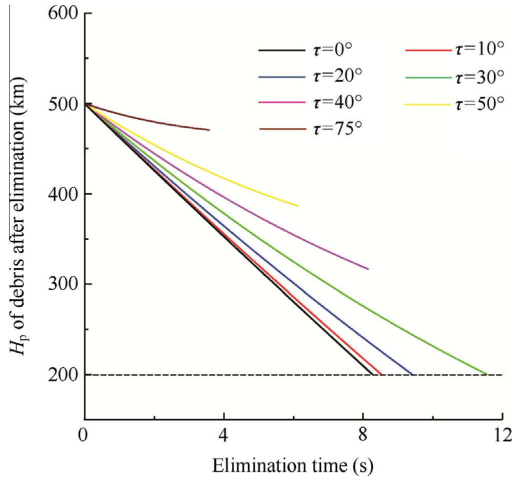

Fig. 7 Elimination of debris in different orbital planes.

In comparison with different projects mentioned above, for eliminating debris of a centimeter magnitude, the repeat frequency of a laser system should be 100 Hz or higher. A higher laser repeat frequency would result in less elimination time. However, a laser system of a too high frequency would cause difficulties such as heat dissipation and high cost. Therefore, the optimal laser repeat frequency is 100 Hz.

4.2. Orbital plane of debris

Target debris and a laser system move in separate orbital planes which do not coincide in most cases. Assume that the relative angle of their orbital planes τ is 0°, 10°, 20°, 30°, 40°, 50°, or 75°. When the laser pulse energy is 1 kJ and frequency is 100 Hz, the effect of elimination is shown in Fig. 7. It can be seen in the figure that if the relative angle of their orbital planes is less than 10°, the elimination time is nearly equal to the condition that their orbital planes coincide with each other. The relative angle between orbital planes is an important factor in elimination. It cannot accomplish the elimination mission when the angle is bigger than 40° in the given conditions.

Too big relative angles would result in a rapid increment of the distance between the laser system and the debris. As a result, the distance would be longer than the 100-km operating distance in a short time. The component of the impulse in the orbital plane would be smaller as a result which is against the elimination.

It can be seen that in order to obtain high efficiency, the relative angle between the debris orbit and the laser orbit would be better if less than 30°, and the bigger the relative angle is, the lower the elimination efficiency is.

4.3. Elimination in emergency

A space station is of huge mass and size. Assume that the space station is about 100 m in length and 400 t in weight. It should maneuver at least 100 m to avoid the hypervelocity collision of the debris after receiving a warning 100 km away. The space station would maneuver 100 m in less than 5 s and be equipped with a rocket engine of 3200 kN thrust. However, the acceleration would result the overload of components such as solar arrays. What is more, it would cause an adverse impact to some scientific experiments which need a stable environment. Therefore, the elimination of dangerous debris through laser irradiation is of significance to the stable operation of the space station.

Table 2 Effects of emergency elimination of debris in different orbital planes.

Material	Relative angel of orbital planes (°)	Minimum distance (m)
Aluminum	0	112.6
	10	112.9
	20	113.8
	40	117.6
	90	141.4
Carbon	0	138.1
	10	138.4
	20	139.6
	40	144.2
	90	173.4

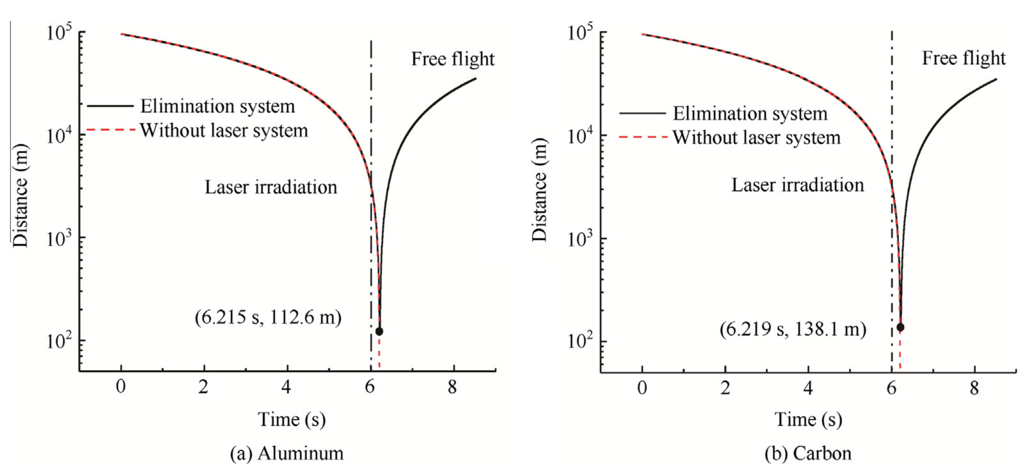

Fig. 8 Effects of elimination in emergency.

Table 3 Project of a space-based laser system.

Assumption		Laser parameters	
Orbital height of laser	420 km	Type	Solid state
Orbital height of space station	400 km	Pulse energy	1 kJ
Operating distance	100 km	Repetition frequency	100 Hz
Debris size	1–10 cm	Mirror diameter	2.44 m
Debris mass	$\leqslant$70 g	Power density	1.39×10^9 W/cm^2
Interaction parameters	Debris material		
	Aluminum		Carbon
Coupling coefficient (N·s/J)	1.4×10^{-5}		2×10^{-5}
Ablation rate (μg/J)	80		10.2

Assume the space station moves in a circular orbit of a 400 km altitude. Laser repetition frequency is 100 Hz and pulse energy is 1 kJ. The target particle and the laser system move in the same orbital plane. The laser system starts to irradiate the debris particle when the distance to the target is 100 km. After the irradiation of 6 s, the minimum distance between the space station and the debris would increase, and the threshold for elimination is 100 m.

The minimum distance is 112.6 m for an aluminum particle and 138.1 m for a carbon particle, as shown in Fig. 8. It would produce obvious effects in comparison with the situation without laser irradiation. Therefore, the laser system can meet the requirement for elimination in emergency.

The elimination effect is shown in Table 2. The debris and the space station moves in different orbital planes. The elimination effect is better when the debris and the space station move in different orbital planes, and a bigger relative angle would lead to a longer minimum distance after laser irradiation. As a result, the laser system can accomplish the mission for eliminating debris of 1–10 cm and protecting the space station.

5. Project of a space-based laser system

The project is summarized in Table 3. Results are gained through the simulations analyzed above. In addition, we take the factors such as elimination efficiency and technical feasibility into consideration. The task of the space-based laser system is mainly to protect the space station from the collision of dangerous debris. The energy consumed by the laser system is supplied from the earth regularly.

6. Conclusions

(1) 100 Hz is demonstrated as the candidate repeat frequency for a space-based laser system. A laser with a lower repeat frequency could not succeed in eliminating while a higher frequency would increase costs.

(2) The relative angle between the debris orbit and the laser orbit would be better if less than 30°. A bigger relative angle would lower the elimination efficiency. After the irradiation of the laser system, the minimum distance between the debris and the laser is longer than 100 m. The laser system can accomplish the mission for eliminating debris of 1–10 cm and protecting the space station.

(3) A space-based laser system is proved to be an appropriate method to eliminate debris that poses a threat to a space station.

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